Components in wireless technology, 5XTC0

Module 7
Exercise: System level design

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Where innovation starts

Outline

- System level design

Formula sheet (1/3)

Power delivered to the load	$P_L = \frac{\lvert V_2^- \rvert^2}{2Z_0}\left(1-\lvert\Gamma_L\rvert^2\right)$
Input power to the network	$P_{in} = \frac{\lvert V_1^+ \rvert^2}{2Z_0}\left(1-\lvert\Gamma_{in}\rvert^2\right)$
Input and output reflection coefficients of a transistor with a source and load: general case	$\Gamma_{in} = \frac{V_1^-}{V_1^+} = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1-S_{22}\Gamma_L}$ $\Gamma_{out} = \frac{V_2^-}{V_2^+} = S_{22} + \frac{S_{12}S_{21}\Gamma_S}{1-S_{11}\Gamma_S}$
Input and output reflection coefficients of a transistor with a source and load: unilateral case	$\Gamma_{in} = \frac{V_1^-}{V_1^+} = S_{11}$ $\Gamma_{out} = \frac{V_2^-}{V_2^+} = S_{22}$
Gain of the input matching network	$G_S = \frac{1-\lvert\Gamma_S\rvert^2}{\lvert 1-\Gamma_{\text{in}}\Gamma_S\rvert^2}$
Gain of the output matching network	$G_L = \frac{1-\lvert\Gamma_L\rvert^2}{\lvert 1-S_{22}\Gamma_L\rvert^2}$
Gain of the transistor (unilateral case)	$G_0 = \lvert S_{21}\rvert^2$
Transducer gain of the basic amplifier circuit (input matching, unilateral transistor, output matching)	$G_T = G_S G_0 G_L$ $G_{T,dB} = G_{S,dB} + G_{0,dB} + G_{L,dB}$
Maximum gain of the input and output matching networks	$G_{S_{\max}} = \frac{1}{1-\lvert S_{11}\rvert^2},$ $G_{L_{\max}} = \frac{1}{1-\lvert S_{22}\rvert^2}.$
Maximum transducer power gain, unilateral case	$G_{TU_{\max}} = \frac{1}{1-\lvert S_{11}\rvert^2}\lvert S_{21}\rvert^2\frac{1}{1-\lvert S_{22}\rvert^2}$
Normalized gain factors g_s and g_L	$g_S = \frac{G_S}{G_{S_{\max}}} = \frac{1-\lvert\Gamma_S\rvert^2}{\lvert 1-S_{11}\Gamma_S\rvert^2}(1-\lvert S_{11}\rvert^2),$ $g_L = \frac{G_L}{G_{L_{\max}}} = \frac{1-\lvert\Gamma_L\rvert^2}{\lvert 1-S_{22}\Gamma_L\rvert^2}(1-\lvert S_{22}\rvert^2).$
Center and radius of the constant gain circle for the input matching network	$C_S = \frac{g_S S_{11}^*}{1-(1-g_S)\lvert S_{11}\rvert^2},$ $R_S = \frac{\sqrt{1-g_S}\,(1-\lvert S_{11}\rvert^2)}{1-(1-g_S)\lvert S_{11}\rvert^2}$
Center and radius of the constant gain circle for the output matching network	$C_L = \frac{g_L S_{22}^*}{1-(1-g_L)\lvert S_{22}\rvert^2},$ $R_L = \frac{\sqrt{1-g_L}\,(1-\lvert S_{22}\rvert^2)}{1-(1-g_L)\lvert S_{22}\rvert^2}$

Formula sheet (2/3)

Power delivered to the load	$P_L = \frac{\lvert V_2^- \rvert^2}{2Z_0}\left(1 - \lvert \Gamma_L \rvert^2\right)$
Input power to the network	$P_{in} = \frac{\lvert V_1^+ \rvert^2}{2Z_0}\left(1 - \lvert \Gamma_{in} \rvert^2\right)$
Input and output reflection coefficients of a transistor with a source and load: general case	$\Gamma_{in} = \frac{V_1^-}{V_1^+} = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L}$ $\Gamma_{out} = \frac{V_2^-}{V_2^+} = S_{22} + \frac{S_{12}S_{21}\Gamma_S}{1 - S_{11}\Gamma_S}$
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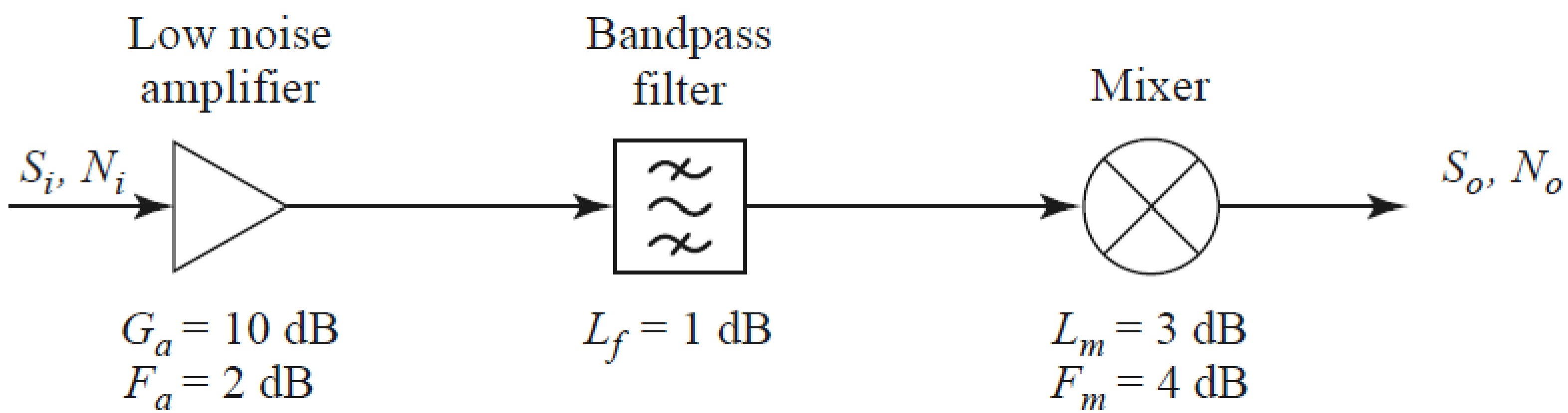
Maximum gain of the input and output matching networks	$G_{S_{\max}} = \frac{1}{1 - \lvert S_{11} \rvert^2},$ $G_{L_{\max}} = \frac{1}{1 - \lvert S_{22} \rvert^2}.$
Maximum transducer power gain, unilateral case	$G_{TU_{\max}} = \frac{1}{1 - \lvert S_{11} \rvert^2}\lvert S_{21} \rvert^2 \frac{1}{1 - \lvert S_{22} \rvert^2}$
Normalized gain factors g_s and g_L	$g_S = \frac{G_S}{G_{S_{\max}}} = \frac{1 - \lvert \Gamma_S \rvert^2}{\lvert 1 - S_{11}\Gamma_S \rvert^2}\left(1 - \lvert S_{11} \rvert^2\right),$ $g_L = \frac{G_L}{G_{L_{\max}}} = \frac{1 - \lvert \Gamma_L \rvert^2}{\lvert 1 - S_{22}\Gamma_L \rvert^2}\left(1 - \lvert S_{22} \rvert^2\right).$
Center and radius of the constant gain circle for the input matching network	$C_S = \frac{g_S S_{11}^*}{1 - (1 - g_S)\lvert S_{11} \rvert^2},$ $R_S = \frac{\sqrt{1 - g_S}\left(1 - \lvert S_{11} \rvert^2\right)}{1 - (1 - g_S)\lvert S_{11} \rvert^2}$
Center and radius of the constant gain circle for the output matching network	$C_L = \frac{g_L S_{22}^*}{1 - (1 - g_L)\lvert S_{22} \rvert^2},$ $R_L = \frac{\sqrt{1 - g_L}\left(1 - \lvert S_{22} \rvert^2\right)}{1 - (1 - g_L)\lvert S_{22} \rvert^2}$

Formula sheet (3/3)

Three-stage amplifier: **Output noise ($P_{n,total}$), noise factor (F_{total}) noise figure (NF_{total})**	$P_{n,total} = G_{A3}G_{A2}G_{A1}P_{n,in} + G_{A3}G_{A2}P_{n1} + G_{A3}P_{n2} + P_{n3}$ $F_{total} = \frac{P_{n,total}}{G_{A3}G_{A2}G_{A1}P_{n,in}}$ $F_{total} = 1 + \frac{P_{n1}}{G_{A1}P_{n,in}} + \frac{P_{n2}}{G_{A1}G_{A2}P_{n,in}} + \frac{P_{n3}}{G_{A3}G_{A2}G_{A1}P_{n,in}}$ $F_{total} = F_1 + \frac{F_2 - 1}{G_{A1}} + \frac{F_3 - 1}{G_{A1}G_{A2}}$ $NF_{total} = 10\log_{10} F_{total}$ Noise factor of single stage $F_j = 1 + \frac{P_{nj}}{G_{Aj}P_{n,in}}, j = 1,2,3$ Noise figure of single stage $NF_j = 10\log_{10} F_j, j = 1,2,3$
Receiver sensitivity	$P_{sens}\,[dBm] = k_B T_0 B[dBm] + NF_{total}[dB] + SNR[dB]$ $P_{sens}\,[dBm] = -174 + NF_{total} + 10\log_{10} B + SNR$
Conversion Watt to dBm	$P_{sens}\,[dBm] = 10\log_{10}\frac{P_{sens}\,[Watt]}{1mWatt}$ $P_{sens}\,[dBm] = 10\log_{10}\frac{P_{sens}\,[Watt]}{10^{-3}Watt}$
Gain conversion from linear to dB	$G\,[dB] = 10\log_{10} G$

Problem 1

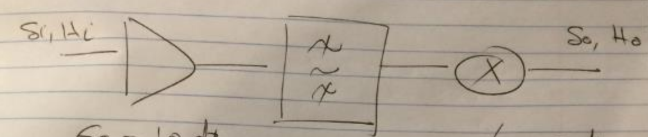


System is at temperature T_0=*17º (290K)*
Impedance of 50 Ω
IF bandwidth of 10 MHz

1) Compute the <u>overall noise figure</u> of this system
2) If the input noise power from a feeding antenna is $N_i = kT_AB$, where T_A= 150 K, find the <u>output noise power</u> in dBm
3) If we require a minimum signal-to-noise ratio (SNR) of 20 dB at the output of the receiver, what is the <u>minimum signal voltage</u> that should be applied at the receiver input?

Problem 1: Solution (1/2)

Example: Wireless receiver



$G_a = 10$ dB
$F_a = 2$ dB → $NF_a = 2$ dB

$L_f = 1$ dB

$L_m = 3$ dB
$F_m = 6$ dB → $NF_m = 6$ dB

$NF = 10 \log F$

1) $$F_{total} = F_a + \frac{F_m - 1}{G_a \cdot L_f}$$

It has to be noise factor

It has to be linear gain not in dB $G_a[dB] = 10 \log G_a$

~~$F_{total} = 10^{NF}$~~

$$F_{total} = 10^{NF_a/10} + \frac{10^{NF_m/10} - 1}{10^{G_a/10} \cdot 10^{-L_f/10}}$$

$$F_{total} = 1,58 + \frac{1,51}{10 \cdot 0.8}$$

$$F_{total} = 1,58 + 0,2 = 1,78$$

$$NF_{total} = 10 \log F_{total} = 2,5 \text{ dB}$$

1

2. $$F = 1 + \frac{T_e}{T_o}$$

System is 50 Ω at T_o temperature
$T_o = 290$ K

$$T_e = (F - 1) \cdot T_o$$

$$T_e = (1.78 - 1) \cdot T_o = 0.78\, T_o$$

$$N_{i,total} = k_B \cdot (T_A + T_e) \cdot B$$

$$N_{o,total} = N_{i,total} \cdot G_{total}$$

$$N_{o,total}[dBm] = N_{i,total}[dBm] + G_{total}[dB]$$

$$G_{total}[dB] = G_a - L_f - L_m = 6 \text{ dB}$$

$$N_{i,total}[dBm] = 10 \log \frac{k_B \cdot (T_A + T_e) \cdot B}{1 \text{ mW}}$$

$k_B = 1.38e^{-23}$ J/K
$T_A = 150$ K
$T_e = 0.78 \cdot 290 \text{ K} = 226,2$ K
$B = 10$ MHz

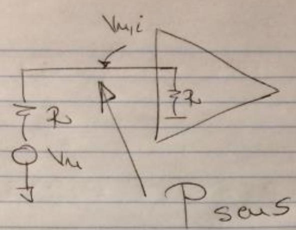
$$N_{i,total}[dBm] = -102,8 \text{ dBm}$$

$$N_{o,total}[dBm] = -102,8 + 6 = \cancel{-96,8 \text{ dBm}}$$

$$N_{o,total}[dBm] = -96.8 \text{ dBm}$$

Problem 1: Solution (2/2)

3.



$V_n^2 = 4kT_0R$

$V_{ni} = \frac{V_n}{2}$

$T_0 = 290K$

$R = 50\Omega$

$N_i = \frac{(V_{ni})^2}{R} = \frac{V_n^2}{4R} = kT_A$

After taking bandwith into account

$N_i = kT_0B$ in bandwidth B

$F = \frac{N_i + N_e}{N_i} = \frac{N_{i,total}}{N_i}$ → total noise at input

$N_{i,total} = F \cdot N_i = F \cdot k \cdot T_0 \cdot B$

$\frac{P_{sens}}{N_{i,total}} = SNR$

$P_{sens} = N_{i,total} \cdot SNR$

$P_{sens} = F \cdot k \cdot T_0 \cdot B \cdot SNR$

$P_{sens}[dBm] = 10\log\frac{P_{sens}}{1mW}$

$P_{sens}[dBm] = 10\log\left(\frac{kT_0}{1mW} \cdot F \cdot B \cdot SNR\right)$

$kT_0[dBm] = 10\log\frac{kT_0}{1mW} = -174\ dBm/Hz$

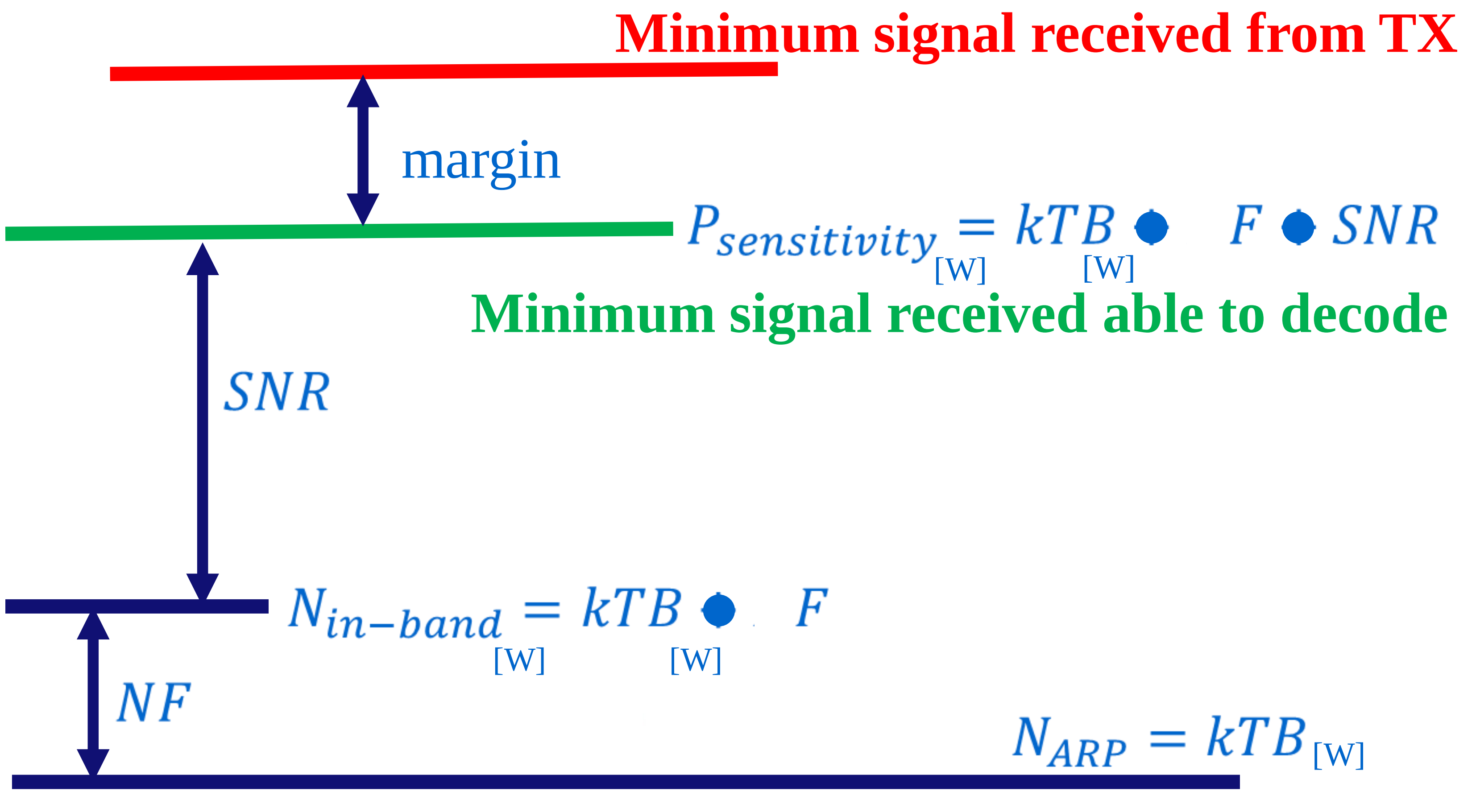
$P_{sens} = -174\frac{dBm}{Hz} + 10\log F + 10\log B + 10\log SNR$

$P_{sens} = -174\frac{dBm}{Hz} + NF + 10\log B + SNR[dB]$

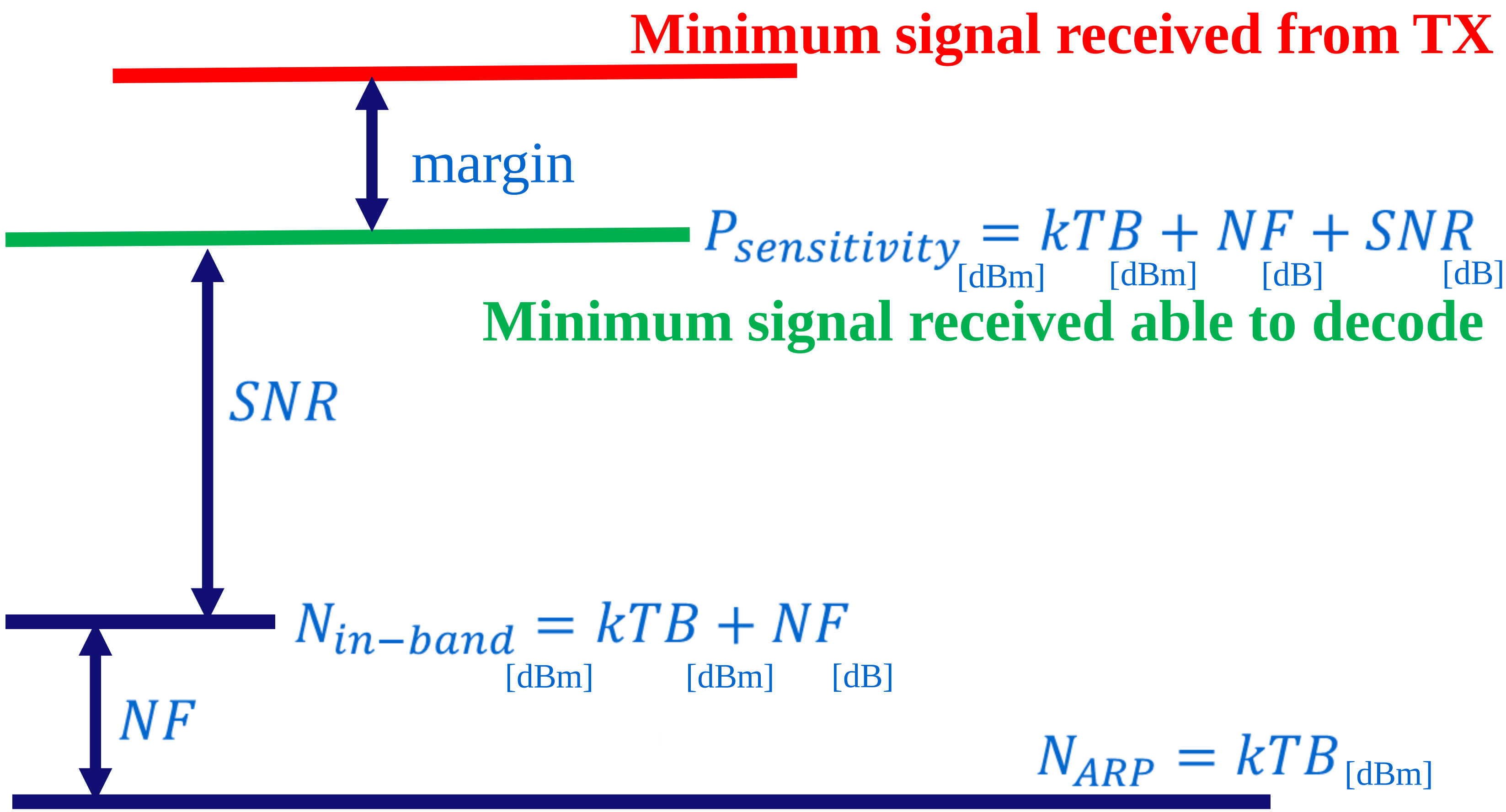
$P_{sens} = -174 + 2.5 + 70 + 20$

$P_{sens} = -81.5\ dBm$

Receiver sensitivity in Watts: graphical representation

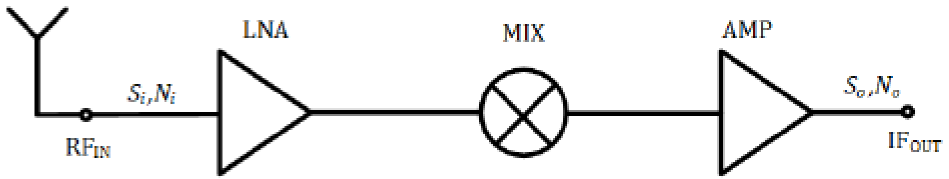


Receiver sensitivity in dBm: graphical representation



Problem 2

The block diagram of the wireless receiver is shown in figure below. The data describing the wireless receiver are provided in the text following the figure. The wireless receiver consists of Low Noise Amplifier (LNA), Mixer (MIX) and Amplifier (AMP). *Si* and N_i denote signal and noise at the RF input (RF_{IN}). S_o and N_o denote signal and noise at the IF output (IF_{OUT}).



$LNA\ gain: G_{LNA}[dB] = 15dB$

$LNA\ noise\ figure: NF_{LNA} = 2dB$

$MIX\ gain: G_{MIX}[dB] = 10dB$

$MIX\ noise\ figure: NF_{MIX} = 10dB$

$AMP\ gain: G_{AMP}[dB] = 20dB$

$AMP\ noise\ figure: NF_{AMP} = 5dB$

$System\ temperature: T_0 = 290K$

$IF\ bandwidth: B = 10MHz$

$Boltzmann\ constant: k_B = 1.38 \cdot 10^{-23} \frac{Watt \cdot s}{K}$

a) Calculate the overall noise figure (*NF*) of the wireless receiver.
b) Which block in wireless receiver has the largest impact on the overall noise figure? Explain your answer.
c) If the input noise power from a feeding antenna is $Ni = k_B T_0 B$, find the output noise power and express it in dBm.
d) If a minimum signal-to-noise ratio (SNR) of 20dB is required at the IF output (IF_{OUT}), what is the minimum signal (so called receiver sensitivity) that should be applied at the RF input (RF_{IN}). Express the receiver sensitivity in dBm.

Problem 2: Solution (1/2)

a) $G_{LNA}[dB] = 15\,dB \Rightarrow G_{LNA} = 10^{15/10} = 31{,}62$

$G_{MIX}[dB] = 10\,dB \Rightarrow G_{MIX} = 10^{10/10} = 10$

$G_{AMP}[dB] = 20\,dB \Rightarrow G_{AMP} = 10^{20/10} = 100$

$NF_{LNA} = 2\,dB \Rightarrow F_{LNA} = 10^{2/10} = 1{,}58$

$NF_{MIX} = 10\,dB \Rightarrow F_{MIX} = 10^{10/10} = 10$

$NF_{AMP} = 5\,dB \Rightarrow F_{AMP} = 10^{5/10} = 3{,}16$

$\cancel{F_{total} = 1 + (F_{LA}}$

$$F_{total} = F_{LNA} + \frac{F_{MIX} - 1}{G_{LNA}} + \frac{F_{AMP} - 1}{G_{LNA} \cdot G_{MIX}}$$

$$F_{total} = 1.58 + \frac{10 - 1}{31.62} + \frac{3.16 - 1}{31.62 \cdot 10}$$

$$F_{total} = 1.58 + 0.28 + 0.0068$$

$$F_{total} = 1.86$$

$$NF_{total} = 10 \cdot \log_{10} F_{total}$$

$$NF_{total} = 10 \log_{10} 1{,}86 = 2.71\,dB$$

Problem 2: Solution (2/2)

b) LNA dominates the noise figure
The impact of other blocks is
reduced by gain of ~~blocks~~
preceding stages (stages
before)

c) $F_{total} = 1 + \frac{T_e}{T_o}$

$T_e = (F_{total} - 1)\, T_o$

$N_{i,total} = k_B \cdot B\, (T_o + T_e)$

$N_{i,total} = k_B \cdot B \cdot T_o \cdot F_{total}$

$N_{i,total} = 1.38 \cdot 10^{-23} \frac{Watt \cdot s}{K} \, 10^{7} \frac{1}{s} \, 290K \cdot 1.86$

$N_{i,total} = 7.44 \cdot 10^{-14}\, Watt = 74{,}4\, fWatt$

$N_{i,total}[dBm] = 10 \log \frac{N_{i,total}}{1\, mWatt}$

$N_{i,total}[dBm] = -101{,}28\, dBm$

$N_{o,total}[dBm] = N_{i,total}[dBm] + G_{total}$

$G_{total}[dB] = G_{LNA} + G_{MIX} + G_{AMP} = 45 dB$

$N_{o,total}[dBm] = -56{,}28\, dBm$

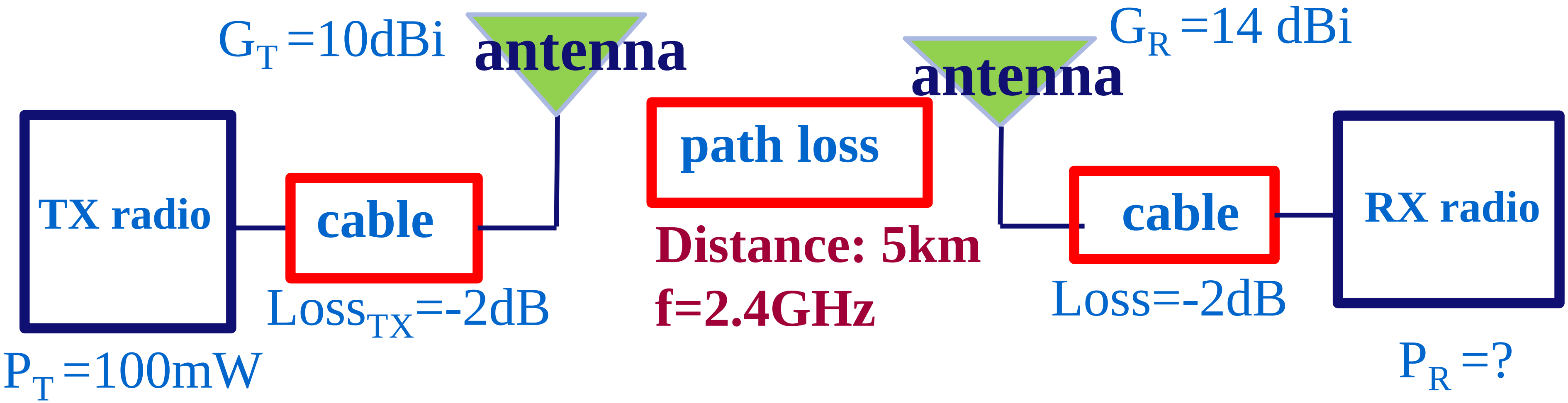
(2)

d) $P_{sens} = -174 + NF_{total} + 10 \log_{10} B + SNR$

$P_{sens} = -174 + 2.71 + 70 + 20$

$P_{sens} = -81{,}29\, dBm$

Problem 3: Calculate the received power



Transmit power	P_t	**+20dBm**
Transmit antenna line loss	$(-)L_t$	**-2dB**
Transmit antenna gain	G_t	**+10dBi**
Path loss (free-space)	$(-)L_0$	**-114dB @ 5km @ 2.4GHz**
Atmospheric attenuation	$(-)L_A$	negligible
Receive antenna gain	G_r	**+14dBi**
Receive antenna line loss	$(-)L_r$	**-2dB**
	=P_R	**-74dBm**

Problem 3: Solution

$P_t = P_T[dBm] + Loss\_Tx + G_T$

$P_T[dBm] = 10\log_{10}\frac{100\,mW}{1\,mW} = 20\,dBm$

$L_t = Loss\_Tx = -2\,dB$

$G_t = G_{Tx} = 10\,dBi$

$\rightarrow \boxed{P_t = 20 - 2 + 10 = 28\,dBm}$

radiated power

$Path\ loss_{[dB]} = 10\log\left(\frac{\lambda}{4\pi R}\right)^2$

$Path\ loss[dB] = 20\log\frac{(c/f)}{(4\pi\cdot R)}$

$c = 3\cdot 10^8\ m/s$

$f = 2.4\ GHz$

$R = 5\ km = 5000\ m$

$\rightarrow \boxed{Path\ loss = 20\log(2\cdot 10^{-6}) = -114\ dB}$

$P_R = P_t + Path\ loss + L_r + G_r$

$L_r = -2\ dB,\ G_r = 14\ dBi \Rightarrow \boxed{P_R = -74\ dBm}$